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Application of Diffraction Corrections to Blackbody Sources

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Calspan Corporation/AEDC Operations

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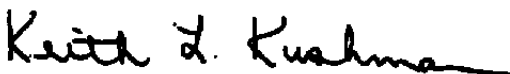
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13. ABSTRACT (Maximum 200 words) In 1974, the National Bureau of Standards (now the National Institute of Standards and Technology) published Technical Note 594-8, stating that diffraction losses should be accounted for in calculating the radiometric output of IR sources. Since 1979, a diffraction correction has been applied to the radiometric output for all cavity-type blackbody sources in use at Arnold Engineering Development Center. The theoretically predicted source diffraction losses were examined and compared to experimental data obtained during the calibration of a typical AEDC source. The results revealed that the experimental data do not support the use of currently available diffraction correction theories. At this time, the use of diffraction corrections is not recommended for AEDC blackbody sources.				
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PREFACE

The work reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC). The results were obtained by Calspan Corporation/AEDC Operations, operating contractor for the Aerospace Flight Dynamics testing facility at the AEDC, AFSC, Arnold Air Force Base, Tennessee under AEDC Project Number DD43VW (Calspan Project Number V32L-FD). The Air Force Project Manager was Capt. Seth Shepherd, AEDC/DOTR. This report describes the work effort initiated in December 1990 and completed in March 1991. The manuscript was submitted for publication on May 17, 1991.

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1.0 INTRODUCTION

Spaceborne sensors that look out into space operate in a low-pressure environment and view a very low infrared (IR) background. Calibration of these types of sensors, or their focal plane assemblies, is normally accomplished in vacuum chambers having an optically tight, cryogenically cooled liner. A typical facility for calibrating Long Wavelength Infrared (LWIR) sensors is described in Ref. 1. A similar facility for calibrating LWIR focal plane arrays is described in Ref. 2. Both of these facilities consist of a vacuum chamber, optically tight GHe-cooled (20 K) liner, and cavity-type IR sources. The IR blackbody sources used in these facilities are generally conical cavities with a small circular output aperture. The source intensity is defined by the cavity temperature and the aperture area (Refs. 3-5). Knowledge of the radiometric output of the blackbody is critical to calibration of the sensors and focal planes.

The use of small circular apertures ($< 2\text{E}^{-2}\text{-cm-diam}$) with IR blackbody cavity sources presents the possibility of radiation losses caused by diffraction effects. This is because the aperture diameter is relatively small as compared to the radiation wavelength (nominally $1\text{E}^{-3}\text{ cm}$). In 1974, the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) published a Technical Note (Ref. 6) that indicated that diffraction losses should be accounted for in calculating the radiometric output of IR sources. Since 1979, the diffraction correction has been applied to the radiometric output for all cavity-type IR sources in use at AEDC (Ref. 7). The diffraction correction was in the form of a correction factor that was dependent on the source geometry and the cavity temperature. Use of the diffraction correction factor for IR sources, as defined in Ref. 6, continued at AEDC through the 1980's.

A variable-aperture blackbody source was developed at AEDC in 1990 for use as an AEDC calibration standard. This source was calibrated at AEDC against a fixed-aperture IR source (AEDC standard with calibration traceability to NIST), prior to being sent to NIST for absolute calibration. The results of this calibration indicated that the diffraction correction in use at AEDC may be inducing errors in the calculation of the source radiometric output. The variable-aperture IR source was then calibrated at NIST (February 1990). The NIST calibration report included a tabulation of diffraction corrections that were used in the source calibration calculations. The NIST diffraction correction factors included contributions from both the AEDC source and the NIST facility. The magnitude of the diffraction correction factors provided by NIST was less than half of those calculated at AEDC. As a result of the AEDC calibration results and the NIST-provided data, it was decided that an investigation of the use of diffraction corrections for IR point sources was needed.

This report provides information relative to the use of diffraction corrections for IR sources. Experimental source calibration data are presented to evaluate the various analytical methods in popular use.

2.0 BLACKBODY SOURCE

2.1 DESCRIPTION

The source (Fig. 1) was a blackbody radiator equipped with variable apertures. The cavity was of a conical/re-entrant cap configuration (Fig. 1a). The diameter of the opening in the re-entrant cap was 0.177 in. The interior of the cavity was anodized to achieve a surface emissivity greater than 0.95. The effective emissivity of the cavity was calculated to be greater than 0.999 (Gouffe method). The source was heated with platinum wire wound around the cavity core. The maximum operating temperature was 500 K. A stainless-steel radiation shield and support provided thermal isolation between the source core and its low-temperature mount. All internal surfaces of the shield were polished to reflect the radiated energy from the heater core back on itself. The cavity core was instrumented with two temperature sensors (platinum resistance thermometers) embedded deep inside the cavity block.

The various pinhole apertures which could be selected were mounted on an aperture wheel (Fig. 1b). The distance between the blackbody cavity opening and the aperture wheel was 0.25 in. The aperture wheel was constructed of aluminum and contained six apertures and a blank position (Table 1). Increasing the aperture size provided a range of source outputs. Position of the aperture wheel was controlled by a bidirectional stepping motor. A rotary potentiometer was used to monitor the wheel angular position (Fig. 1).

2.2 RADIOMETRIC OUTPUT

The radiometric output from a blackbody source is determined by the source radiance. The source radiance (L) is determined by the integration of Planck's law of radiation (Refs. 3-5) over the wavelength interval of interest. Integrating Planck's law over wavelength limits from zero to infinity gives the total blackbody radiant emittance (M), the flux radiated into a hemisphere (Stefan-Boltzmann law). For a Lambertian emitter, i.e., one that follows Lambert's cosine law, the source radiance is the radiant emittance divided by π . This leads to the expression for source radiance.

$$L = \frac{(\epsilon\sigma T^4)}{\pi} \quad (1)$$

The terms ϵ and σ in Eq. (1) refer to the blackbody emissivity and the Stefan-Boltzmann constant ($5.67\text{E}-12 \text{ w/cm}^2\text{T}^4$), respectively. Figure 2 is a schematic presentation that is useful

for a radiometric analysis. The theoretical irradiance incident on the detector is the radiance (L) of the source times the area of the source aperture (A_p), divided by the aperture-to-detector distance (a) squared (Refs. 3-5).

$$E = \frac{(LA_p)}{a^2} \quad (2)$$

The above expression for irradiance neglects possible diffraction losses caused by the physical size of the pinhole aperture. Diffraction would cause a reduction of the irradiance at the detector. The decrease in calculated irradiance can be accounted for by the use of a diffraction constant (K_d).

$$E = \frac{(K_d LA_p)}{a^2} \quad (3)$$

The next section of this report will present several theoretical techniques for determining the magnitude of the diffraction constant.

3.0 DIFFRACTION METHODS

3.1 METHOD OF FUSSELL

The value of the diffraction constant in Eq. (3) can be determined using the method prescribed by Fussell (Ref. 6). The mathematical formulas presented in Ref. 6 are refinements of the basic Fraunhofer on-axis diffraction formula (Ref. 8). The diffraction loss (E'_{\min}) is defined for a point detector on axis whose distance from the source aperture is at least ten times the source aperture distance. The diffraction loss E'_{\min} is given as a percentage of the irradiance that would be present at the detector in the absence of diffraction.

$$E'_{\min} = (2.1296 \text{ bd})(\pi^2 DT(d^2 - D^2))^{-1} \quad (4)$$

The terms in Eq. (4) are defined in Fig. 2. Since E'_{\min} is not a function of the source-to-detector distance, it can be tabulated for any source design. Note that the emitting wavelength is not explicitly presented in Eq. (4). For Planck blackbody spectral radiance at temperature T, the effective wavelength is expressed in microns by the function $5324/T$, where T is in degrees Kelvin. This function was included in the derivation of Eq. (4). For the mechanical dimensions of the source described in Section 2.1, Eq. (4) may be reduced to

$$E'_{\min} = \frac{24.5}{T} \quad (5)$$

The diffraction constant is defined as $1 - E'_{\min}$. The diffraction constants for the apertures of the source described in Section 2.2 are presented in Table 2 for a source temperature of 500 K.

3.2 METHOD OF STEEL, DE, AND BELL

Reference 9 presents another treatment of radiometric errors caused by circular apertures where both the source and the detector are of finite size. Both the source and detector are circles of finite size centered on the axis of the diffraction aperture (Fig. 3). A circular source S emits incoherent radiation of wavelength λ . The source is of radius a and at a distance s from a circular aperture A of radius b (Fig. 3). At a further distance s' is a circular detector D of radius a' . The source and detector subtend angular semiapertures $\alpha = a/s$ and $\alpha' = a'/s'$, respectively, at the center of the aperture. It is also convenient to introduce the angle $\beta = b(1/s + 1/s')$. All of these angles are assumed to be small, so that scalar diffraction theory can be used.

Two cases are of interest in the study of diffraction corrections in radiometry. In the first, the detector is intended to receive all of the radiation from the source that passes through the aperture. For this condition

$$\beta < (\alpha' - \alpha) \quad (6)$$

The reciprocal case of Case 1, to which the same theory applies but with α and α' interchanged, is that in which the source is large enough to fill the aperture completely when it is viewed by a detector at some distance in front of it. The notation for the reciprocal case is presented in Fig. 3.

The second case of practical interest occurs when the detector lies wholly within the fully irradiated region. Its angular size satisfies the condition

$$\beta > (\alpha' - \alpha) \quad (7)$$

Instead of angles α , α' , and β , it is convenient to define the quantities w , w' , and u .

$$w = kb\alpha \quad (8)$$

$$w' = kb\alpha' \quad (9)$$

$$u = kb\beta \quad (10)$$

where k is the propagation constant $2\pi/\lambda$. The effective wavelength, λ , is expressed in centimeters by the function $0.5324/T$.

The blackbody source configuration under study is Case 1. The diffraction correction for this case is defined by $F_1(u, w, w')$ presented in Ref. 9. The integral equation that defines $F_1(u, w, w')$ requires numerical integration for an exact solution. A simplified solution to the integral was presented as an approximate solution to the complex integral.

$$F_1(u, w, w') = 1 - (1/(2DW)) \ln |(w' + w)^2 - u^2| / |(w' - w)^2 - u^2| \quad (11)$$

The value of $F_1(u, w, w')$ calculated by Eq. (11) does not differ by more than $5E^{-5}$ from the value found by numerical integration for u and $v = w + w'$ given by

$$v^2 - u^2 > 6,000 \quad (12)$$

Conditional limits are generally calculated as a means of evaluating the validity of Eq. (11).

$$1 > F_1(u, 0, w') > F_1(u, w, w') > F_1(u, 0, w' - w) \quad (13)$$

The diffraction correction coefficients for the IR source, as calculated by the methods of Ref. 9, are presented in Table 3. The fixed parameter values are listed at the top of the table, and the source aperture diameters are listed in the second column. Note that u is less than $w' - w$, and that w' is greater than w . Therefore, two of the test conditions are satisfied. The diffraction correction $F_1(u, w, w')$ for aperture 1 was 0.952, or a 4.8-percent diffraction loss. The upper and lower limits, $F_1(u, 0, w')$ and $F_1(u, 0, v)$, for the diffraction coefficient do not bound $F_1(u, w, w')$. There are two possible reasons that $F_1(u, w, w')$ is not bounded by the upper and lower limits. First, the value $(v^2 - u^2)$ is only 174, which is not within the condition that it be greater than 6,000. This means that the value of $F_1(u, w, w')$ should be calculated by numerical integration, which is beyond the scope of this report. Another possibility for error in the analysis is the fact that the theory is based on small values for all angles. The full angle that the source cavity opening subtends from the aperture is 35 deg, which is definitely too large to meet the small angle approximation. However, even though $F_1(u, w, w')$ is not bounded by its limits, its value (0.952) is to three digits the same as the limits.

3.3 METHOD OF BOIVIN

The diffraction correction associated with a circular aperture in the case of an extended source and a detector located in the fully illuminated region (Case 2 above) was presented in Ref. 10. Boivin indicates that the intensity distribution formula used in Ref. 9 was incorrect

for the central region of the diffraction pattern. The methodology presented in Ref. 10 is basically the same as that used in Ref. 9. The difference is in the final result for $F_2(u, w, w')$. The subscript in $F_2(u, w, w')$ denotes Case 2. For $w' > w$

$$F_2(u, w, w') = 1 - 2/(\pi w') \quad (14)$$

Two assumptions were made in the derivation of Eq. (14). The first was that $u > w' + w$, and second that $w' > w$. The first condition states that the detector lies wholly in the fully illuminated region (Case 2).

The physical configuration for the source, aperture, and detector for the experimental setup was for Case 1 reciprocal, and not Case 2. However, since the calculation was simple it was decided to calculate the diffraction correction using Eq. (14). The results are presented in Table 4. Note that all of the similarly identified parameters listed in Table 4 are the same as the corresponding parameters in Table 3. The values for $F_2(u, w, w')$ for each of the apertures are almost identical to the values of $F_1(u, w, w')$ in Table 3. It should be noted that u is not greater than $w' + w$, as required by the derivation of $F_2(u, w, w')$.

4.0 EXPERIMENTAL DATA

The predicted reduction in the radiometric output of an apertured blackbody cavity source with decreasing aperture size needs to be verified experimentally. To this end, several simple experimental measurements were made. A bolometer was used to measure the blackbody source output for each of six source apertures (Table 1). Figure 2 is a schematic representation of the test setup. The bolometer was cooled to nominally 2 K. The test was conducted in an optically tight, cryogenically cooled (> 20 K) vacuum chamber. Test hardware and measurement procedures have been documented elsewhere, and this detail will not be presented here.

The irradiance measured at the bolometer as a function of source aperture is presented for 27 data sets in Table 5. The average measured irradiance and standard deviation for the data sets are presented for each aperture. Note that except for aperture 1, the standard deviation of the repeated measurements is less than 1 percent. The standard deviation of the irradiance measurements for aperture 1 was nominally 2.5 percent.

The source output (i.e., irradiance at the detector) is a linear function of source aperture area in the absence of diffraction. The tabulated data showing the linearity of these measurements are presented in Table 6. Since the measurement dynamic range is nominally two and a half orders of magnitude, the data are plotted using a log/log format (Fig. 4). The slope of the irradiance-area data presented in Fig. 4 is very close to unity, indicating

a linear relationship. Table 6 provides a comparison between the perfectly linear relationship (slope = 1) and the slightly nonlinear relationship (slope = 1.00127). Note that the largest deviation from linearity was only 1.14 percent (aperture 1). This method of calculation does not consider uncertainties in the aperture areas (Table 1). Some of the nonlinearity could result from these errors, but the use of precision apertures limits the possible impact to about 2 percent or less.

A second method of presenting the linearity of the source output is presented in Table 6. The source output is zero when the aperture area is zero. A calibration constant (K) was calculated for each source aperture by dividing the measured irradiance by the source aperture area. The calibration constant for each aperture was compared to the average source constant for all apertures. Note that the deviation from average for the source constant was less than ± 2 percent. Also, there was no noticeable trend in the percent difference with decreasing aperture area (i.e., the percent difference appeared to be random with source area). The measured irradiance was compared to a calculated value using the average calibration constant. The percent difference between the measured and calculated irradiance followed the same trend as that for the calibration constant.

5.0 DISCUSSION OF RESULTS

Theoretical values for the diffraction correction of a blackbody source were calculated for an experimental test case. Methods of several different investigators were used. A summary of the theoretical and experimental results is provided in Table 7. All of the theoretical methods indicate that only the smallest source aperture had a significant diffraction correction (4.8 percent). The experimental data do not verify the results of the theoretical calculations. There was no indication of a departure from linearity for aperture 1 in the experimental measurements. A 4.8-percent decrease in detector signal should have been noticeable for aperture 1, since the standard deviation of 26 measurements was only 2.5 percent.

By intuition alone, it would seem that a diffraction correction is inapplicable for the experimental arrangement presented above (i.e., large cavity source using small output apertures). If the detector is considered to be the source (reciprocity), all rays that are emitted from the detector which pass through the source aperture will be intercepted by the source cavity, unless they are diffracted by more than 15 deg. The energy in rays diffracted by more than 15 deg should be very small with respect to those of the central core.

6.0 CONCLUSIONS

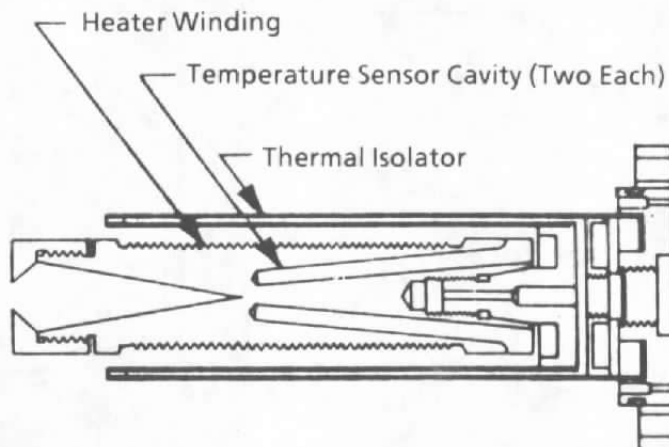
The purpose of this report was to document the results of an investigation relative to the use of diffraction correction constants on blackbody sources used for calibration of IR

sensors and focal planes. The theoretical methods presented indicate a significant diffraction correction (4.8 percent) for the smallest aperture presently in use. A puzzling result of the theoretical evaluation was the fact that all of the theoretical methods produced the same value for the diffraction correction, even if the application of the theory was inappropriate. The experimental results did not validate the theoretical analysis. No diffraction loss was indicated by the experimental measurements. At this time, it is recommended that the use of diffraction corrections be discontinued at AEDC for sources that show no evidence of diffraction by experimental measurements. The problem of diffraction losses in blackbody sources is being re-evaluated both analytically and experimentally at the NIST. The NIST calibration facility has recently improved its system performance. These improvements will allow NIST to measure the output of sources at low temperatures and small apertures, where the theories would call for significant diffraction corrections. At the conclusion of the NIST evaluation, the question of whether to apply diffraction corrections to AEDC blackbody source outputs should be reassessed.

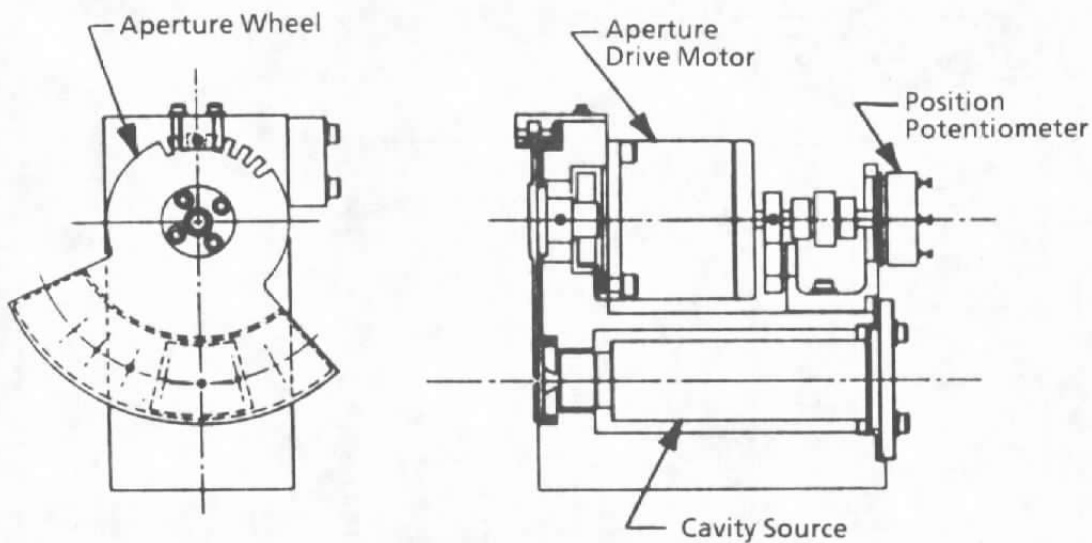
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a. Cavity source



b. Assembly

Figure 1. Blackbody source.

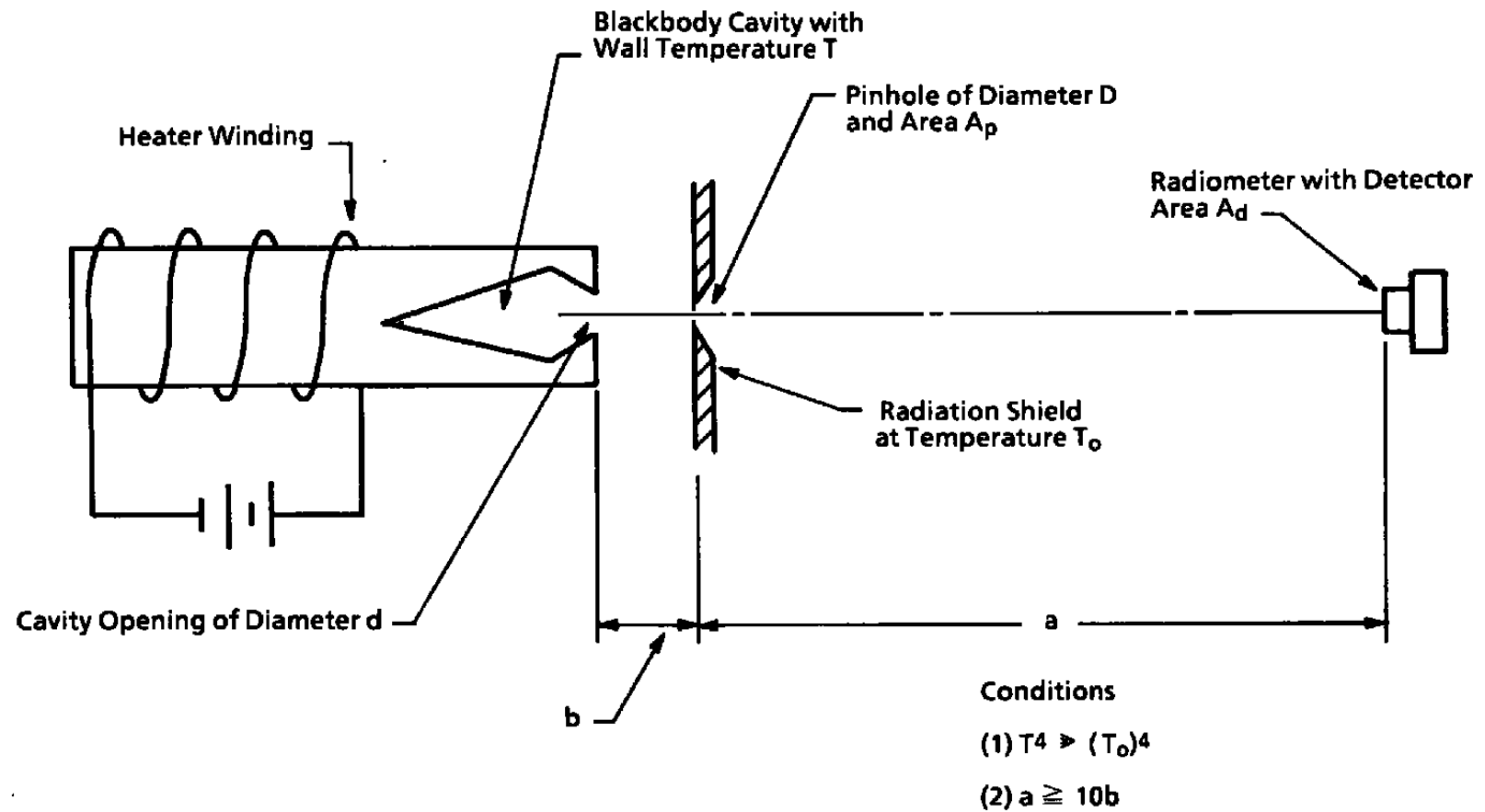
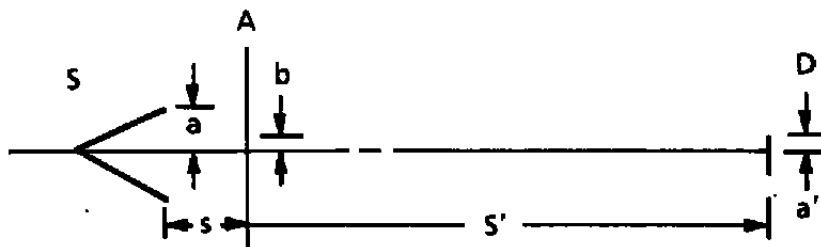
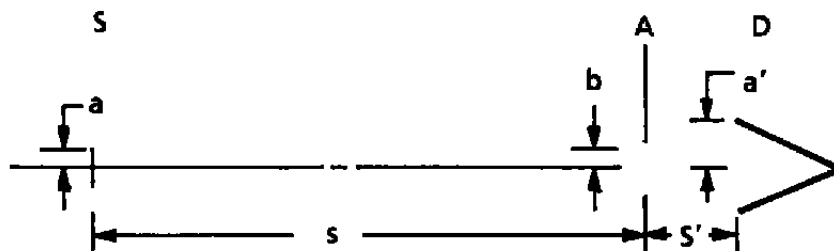


Figure 2. Schematic for analysis of radiometric output.



Source S of radius a is at distance s from a circular aperture A of radius b . Beyond D at distance s' is a receiver D of radius a' .

a. Case 1



By the theorem of reciprocity, exchange S and D.

b. Reciprocal Case 1

Figure 3. Diffraction notation for method of Steel, De, and Bell.

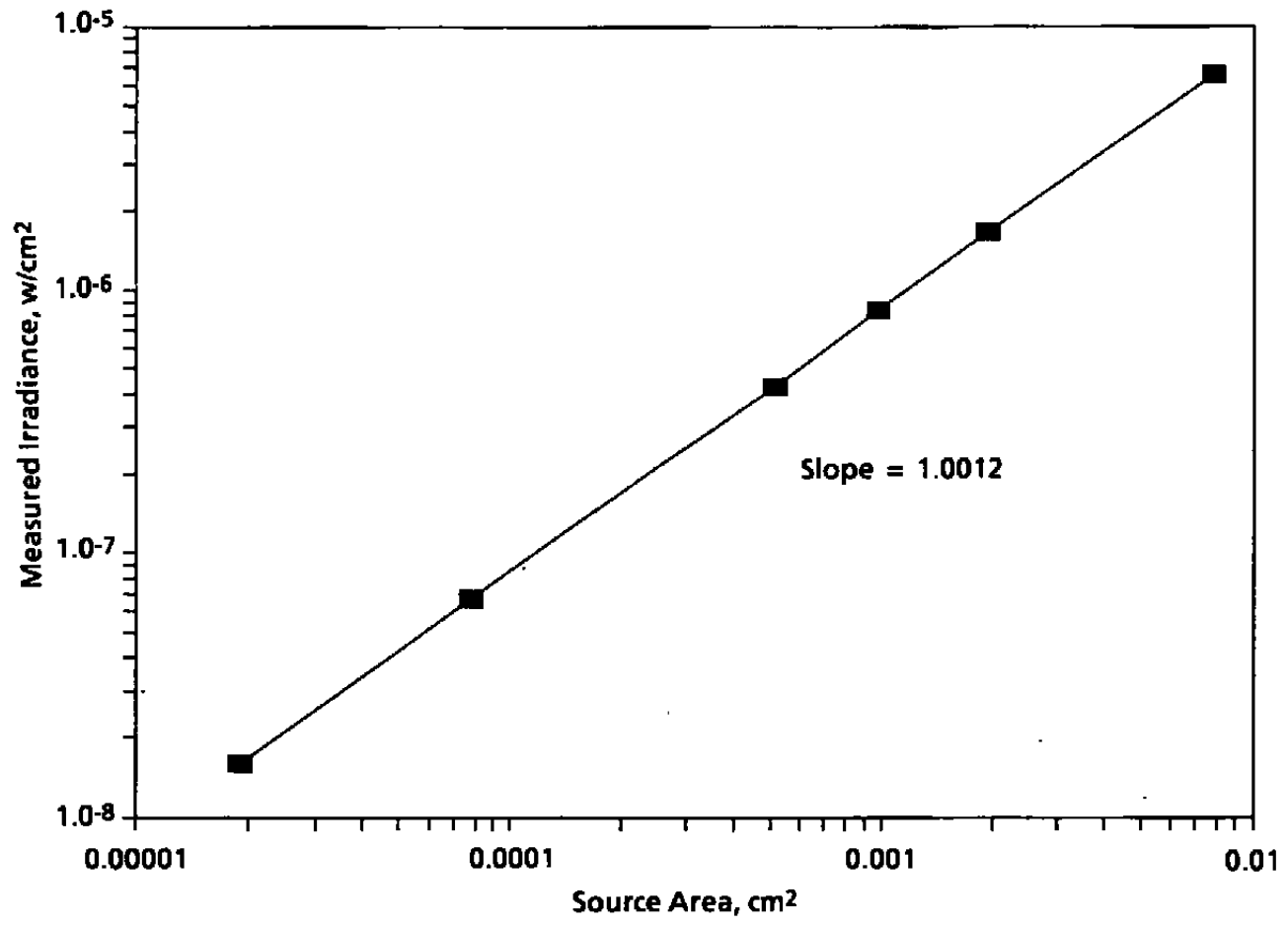


Figure 4. Source output linearity.

Table 1. Blackbody Source Apertures

No.	Diameter, cm		Area, cm ²		Area Uncertainty, percent
	300 K	20 K	300 K	20 K	
1	0.012530	0.012502	1.233E-04	1.228E-04	2.010
2	0.025367	0.025309	5.054E-04	5.031E-04	1.003
3	0.254135	0.253550	5.073E-02	5.049E-02	0.100
5	0.127109	0.126817	1.269E-02	1.263E-02	0.200
6	0.090195	0.089987	6.390E-03	6.360E-03	0.282
7	0.065024	0.064874	3.321E-03	3.306E-03	0.391

**Table 2. Diffraction Constants Using
Fussell Method (Ref. 6)**

Aperture	Kd	1-Kd, percent
1	0.951	4.9
2	0.976	2.4
7	0.990	1.0
6	0.993	0.7
5	0.995	0.5
3	0.996	0.4

Source Temperature = 500 K

Source-to-Aperture Distance = 0.635 cm

Source Diameter = 0.4496 cm

Table 3. Diffraction Constants Using Steel, De, and Bell Method (Ref. 9)

Diffraction Calculations

 $s' = 0.635$ cm $s = 28.7$ cm $2a = 0.1$ cm $2a' = 0.4496$ cm

Temperature = 500 K

 $\text{Lambda} = 0.000106$ cm

Aperture No.	2b, cm	u	w	w'	$\frac{v}{w' - w}$	w + w'	Lower Limit $F_1(u, 0, v)$	Diffraction Correction $F_1(u, 0, w')$	Upper Limit $F_1(u, 0, w')$	1- $F_1(u, w, w')$, percent
1	0.0125	0.371	0.064	13.056	12.992	13.120	0.952	0.951	0.952	4.88
2	0.0253	1.520	0.130	26.426	26.296	26.556	0.975	0.976	0.975	2.42
7	0.0649	10.002	0.334	67.787	67.454	68.121	0.990	0.990	0.990	0.96
6	0.0900	19.234	0.463	94.004	93.542	94.467	0.993	0.993	0.993	0.71
5	0.1268	38.179	0.652	132.441	131.790	133.093	0.995	0.995	0.995	0.52
3	0.2540	153.197	1.306	265.301	263.995	266.606	0.996	0.996	0.996	0.36

Table 4. Diffraction Constants Using Boivin Method (Ref. 10)

Diffraction Calculations

 $s' = 0.635$ cm $s = 28.7$ cm $2a = 0.1$ cm $2a' = 0.4496$ cm

Temperature = 500 K

 $\text{Lambda} = 0.000106$ cm

Aperture No.	2b, cm	u	w	w'	v,w' - w	w + w'	$F_2(u,v,w')$	1- $F_2(u,v,w')$ Percent
1	0.0125	0.371	0.064	13.056	12.992	13.120	0.951	4.88
2	0.0253	1.521	0.130	26.436	26.306	26.566	0.976	2.41
7	0.0649	10.002	0.334	67.787	67.454	68.121	0.991	0.94
6	0.0900	19.230	0.463	93.994	93.531	94.456	0.993	0.68
5	0.1268	38.179	0.652	132.441	131.790	133.093	0.995	0.48
3	0.2540	153.197	1.306	265.301	263.995	266.606	0.998	0.24

Table 5. Source Repeatability Results Irradiance (w/cm²)

Set	Aperture No.					
	1	2	3	5	6	7
3	1.61 ⁻⁸	6.73 ⁻⁸	6.64 ⁻⁶	1.68 ⁻⁶	8.37 ⁻⁷	4.28 ⁻⁷
4	1.62 ⁻⁸	6.78 ⁻⁸	6.61 ⁻⁶	1.68 ⁻⁶	8.41 ⁻⁷	4.33 ⁻⁷
5	1.59 ⁻⁸	6.64 ⁻⁸	6.59 ⁻⁶	1.67 ⁻⁶	8.36 ⁻⁷	4.29 ⁻⁷
6	1.61 ⁻⁸	6.70 ⁻⁸	6.61 ⁻⁶	1.67 ⁻⁶	8.35 ⁻⁷	4.27 ⁻⁷
7	1.60 ⁻⁸	6.68 ⁻⁸	6.60 ⁻⁶	1.67 ⁻⁶	8.33 ⁻⁷	4.26 ⁻⁷
8	ND	6.72 ⁻⁸	6.62 ⁻⁶	1.68 ⁻⁶	8.36 ⁻⁷	4.27 ⁻⁷
9	1.60 ⁻⁸	6.71 ⁻⁸	6.64 ⁻⁶	1.68 ⁻⁶	8.39 ⁻⁷	4.28 ⁻⁷
10	1.61 ⁻⁸	6.70 ⁻⁸	6.61 ⁻⁶	1.67 ⁻⁶	8.33 ⁻⁷	4.26 ⁻⁷
11	1.57 ⁻⁸	6.61 ⁻⁸	6.54 ⁻⁶	1.66 ⁻⁶	8.29 ⁻⁷	4.24 ⁻⁷
12	1.60 ⁻⁸	6.66 ⁻⁸	6.58 ⁻⁶	1.67 ⁻⁶	8.32 ⁻⁷	4.25 ⁻⁷
13	1.60 ⁻⁸	6.65 ⁻⁸	ND	1.67 ⁻⁶	8.38 ⁻⁷	4.30 ⁻⁷
14	1.60 ⁻⁸	6.67 ⁻⁸	ND	1.67 ⁻⁶	8.38 ⁻⁷	4.30 ⁻⁷
15	1.60 ⁻⁸	6.66 ⁻⁸	ND	1.67 ⁻⁶	8.39 ⁻⁷	4.31 ⁻⁷
16	1.50 ⁻⁸	6.59 ⁻⁸	ND	1.66 ⁻⁶	8.36 ⁻⁷	4.31 ⁻⁷
17	1.53 ⁻⁸	6.67 ⁻⁸	6.50 ⁻⁶	1.66 ⁻⁶	8.30 ⁻⁷	4.26 ⁻⁷
18	1.56 ⁻⁸	6.80 ⁻⁸	6.59 ⁻⁶	1.68 ⁻⁶	8.41 ⁻⁷	4.30 ⁻⁷
19	1.61 ⁻⁸	6.83 ⁻⁸	6.54 ⁻⁶	1.67 ⁻⁶	8.31 ⁻⁷	4.27 ⁻⁷
20	1.55 ⁻⁸	6.67 ⁻⁸	6.56 ⁻⁶	1.67 ⁻⁶	8.35 ⁻⁷	4.29 ⁻⁷
21	1.54 ⁻⁸	6.69 ⁻⁸	6.54 ⁻⁶	1.67 ⁻⁶	8.34 ⁻⁷	4.28 ⁻⁷
22	1.56 ⁻⁸	6.59 ⁻⁸	6.40 ⁻⁶	1.65 ⁻⁶	8.23 ⁻⁷	4.22 ⁻⁷
23	1.46 ⁻⁸	6.61 ⁻⁸	6.51 ⁻⁶	1.67 ⁻⁶	8.34 ⁻⁷	4.27 ⁻⁷
24	1.57 ⁻⁸	6.75 ⁻⁸	6.51 ⁻⁶	1.67 ⁻⁶	8.32 ⁻⁷	4.26 ⁻⁷
25	1.64 ⁻⁸	6.78 ⁻⁸	6.51 ⁻⁶	1.67 ⁻⁶	8.32 ⁻⁷	4.27 ⁻⁷
26	1.58 ⁻⁸	6.67 ⁻⁸	6.52 ⁻⁶	1.67 ⁻⁶	8.33 ⁻⁷	4.27 ⁻⁷
27	1.56 ⁻⁸	6.67 ⁻⁸	6.54 ⁻⁶	1.67 ⁻⁶	8.35 ⁻⁷	4.28 ⁻⁷
28	1.55 ⁻⁸	6.64 ⁻⁸	ND	1.68 ⁻⁶	8.42 ⁻⁷	4.33 ⁻⁷
29	1.60 ⁻⁸	6.72 ⁻⁸	ND	1.70 ⁻⁶	8.50 ⁻⁷	4.37 ⁻⁷
Average	1.58 ⁻⁸	6.69 ⁻⁸	6.56 ⁻⁶	1.67 ⁻⁶	8.35 ⁻⁷	4.28 ⁻⁷
Standard Deviation	3.97 ⁻¹⁰	6.15 ⁻¹⁰	5.83 ⁻⁸	9.51 ⁻⁹	5.01 ⁻⁹	3.06 ⁻⁹
Standard Deviation, percent	2.52	0.92	0.89	0.57	0.60	0.71

Table 6. Source Linearity Results**a. Method 1**

Aperture No.	Area, cm ²	Average Measured Irradiance, w/cm ²	Log Area	Log Irrad.	Area ^{1.00127}	Area Diff., percent
1	1.228 ⁻⁴	1.58 ⁻⁸	-3.9109	-7.8013	1.21 ⁻⁴	1.14
2	5.031 ⁻⁴	6.69 ⁻⁸	-3.2984	-7.1746	4.98 ⁻⁴	0.96
7	3.306 ⁻³	4.28 ⁻⁷	-2.4807	-6.3686	3.28 ⁻³	0.72
6	6.360 ⁻³	8.35 ⁻⁷	-2.1965	-6.0783	6.32 ⁻³	0.64
5	1.263 ⁻²	1.67 ⁻⁶	-1.8986	-5.7773	1.26 ⁻²	0.55
3	5.049 ⁻²	6.56 ⁻⁶	-1.2968	-5.1831	5.03 ⁻²	0.38

Slope = 1.00127

b. Method 2

Aperture No.	Area, cm ²	Irradiance (w/cm ²) Meas.	Calc.	Diff., percent	K, (w/cm ² /cm ²)	KDiff., percent
1	1.228 ⁻⁴	1.58 ⁻⁸	1.61 ⁻⁸	-1.60	1.287 ⁻⁴	1.57
2	5.031 ⁻⁴	6.69 ⁻⁸	6.58 ⁻⁸	1.67	1.330 ⁻⁴	-1.69
7	3.306 ⁻³	4.28 ⁻⁷	4.32 ⁻⁷	-1.01	1.295 ⁻⁴	1.00
6	6.360 ⁻³	8.35 ⁻⁷	8.32 ⁻⁷	0.40	1.313 ⁻⁴	-0.40
5	1.263 ⁻²	1.67 ⁻⁶	1.65 ⁻⁶	1.10	1.322 ⁻⁴	-1.12
3	5.049 ⁻²	6.56 ⁻⁶	6.60 ⁻⁶	-0.65	1.299 ⁻⁴	0.64

KAVE = 1.31⁻⁴

Table 7. Summary of Theoretical and Experimental Results

Aperture No.	Theoretical, percent			Experimental, percent	
	Fussel	Steel	Boivin	Method 1	Method 2
1	4.9	4.8	4.8	1.14	1.57
2	2.4	2.4	2.4	0.96	-1.69
7	1.0	1.0	0.9	0.72	1.00
6	0.7	0.7	0.7	0.64	-0.4
5	0.5	0.5	0.5	0.55	-1.12
3	0.4	0.4	0.2	0.38	0.64

NOMENCLATURE

a	Distance or radius, cm
a'	Radius of detector, cm
A_p	Source aperture area, cm ²
b	Distance or radius, cm
d	Cavity opening diameter, cm
D	Diameter of blackbody aperture, cm
E	Irradiance, w/cm ²
D'_{min}	Diffraction loss defined by Fussell
F₁	Diffraction correction, Case 1
F₂	Diffraction correction, Case 2
k	Propagation constant, cm ⁻¹
K_d	Diffraction constant
L	Radiance, w/cm ² -sr
M	Radiant emittance, w/cm ² -sr
S	Distance from source opening to aperture, cm
S'	Distance from aperture to detector, cm
T	Temperature, K
α	Angular semiaperture subtended by source

α'	Angular semiaperture subtended by detector
ϵ	Blackbody emissivity
σ	Stefan-Boltzmann constant, $5.67\text{E-}12 \text{ w/cm}^2\text{K}^4$

Note: Other variables are derived or defined in the text.